Determination of the branching fractions for $\psi(3770) \to D^0\bar{D}^0, D^+D^-, D\bar{D}$ and $\psi(3770) \to \text{non}-D\bar{D}$

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The branching fractions for $\psi(3770) \to D^0\bar{D}^0, D^+D^-, D\bar{D}$ and $\psi(3770) \to \text{non}-D\bar{D}$ are determined based on the cross sections for $\psi(3770)$ and $D\bar{D}$ production measured by BES Collaboration. From its recent publications we determine the branching fractions for $\psi(3770) \to D^0\bar{D}^0, D^+D^-$ and $\psi(3770) \to D\bar{D}$ to be $(52.2 \pm 4.8 \pm 5.5)\%$, $(37.0 \pm 5.0 \pm 4.3)\%$ and $(89.1 \pm 6.9 \pm 9.2)\%$, respectively. The latter one implies the branching fraction for $\psi(3770) \to \text{non}-D\bar{D}$ to be $(10.9 \pm 6.9 \pm 9.2)\%$, corresponding the inclusive non$-D\bar{D}$ partial width $\Gamma(\psi(3770) \to \text{non}-D\bar{D}) = (2.8 \pm 1.8 \pm 2.4)$ MeV. Meanwhile we determine the observed cross section for $non - D\bar{D}$ event production from $\psi(3770)$ decays to be $\sigma^{\text{obs}}(\psi(3770) \to non - D\bar{D}) = (0.72 \pm 0.46 \pm 0.62)$ nb.

I.   INTRODUCTION

The $\psi(3770)$ charmonium state is the lowest-mass resonance above open charmed pair threshold [1]. It is believed to mainly be a mixture of the 1^3D_1 and 2^3S_1 angular momentum eigenstate. This charmonium state is expected to predominately decay into the OZI allowed $D^0\bar{D}^0$ and D^+D^- final states.

However, there is a long-standing puzzle in the $\psi(3770)$ production and decays. Available published data indicate that the measured values of $D\bar{D}$ production cross section at the peak of $\psi(3770)$ resonance fail to fit in the measured values of the cross section for $\psi(3770)$ production. A detail analysis of the experimental data taken at SPEAR shows that about 38% of $\psi(3770)$ does not decay into $D^0\bar{D}^0$ and D^+D^- [2] (see section II for detail). Some new publications about $\psi(3770)$ and $D\bar{D}$ production and decays from BES [3] [4] [5] and CLEO [6] still indicate that $\psi(3770)$ is not saturated by $D^0\bar{D}^0$ and D^+D^- decays.

Measurements of the branching fractions for $\psi(3770) \to D^0\bar{D}^0, D^+D^-, D\bar{D}$ can help for understanding of the decay mechanism of $\psi(3770)$ and for elucidating the exact nature of the $\psi(3770)$. Measurement of the partial width for $\psi(3770) \to \text{non}-D\bar{D}$ decay is essential to clarify the long-standing puzzle of the $\psi(3770)$ production and decays, and is helpful for solving the $\rho - \pi$ puzzle in $\psi(3686)$ decay [7].

Recently, BES published a preliminary result on measurement of the cross section for $\psi(3770)$ production obtained by analyzing a fine cross section scan data sets taken from 3.666 GeV to 3.897 GeV. Based on these modern measurements for both the $\psi(3770)$ and $D\bar{D}$ production at the peak of $\psi(3770)$ resonance and the measurement of the $\psi(3770)$ resonance parameters and with making some necessary corrections for radiative effects, we can determine the branching fractions for $\psi(3770) \to D^0\bar{D}^0, D^+D^-$ and $\psi(3770) \to D\bar{D}$ in a consistent way with the new measured parameters by BES. Meanwhile we can extract the branching fraction for $\psi(3770) \to \text{non}-D\bar{D}$.

In this letter we report the determinations of the branching fractions.

II. $\psi(3770)$ RESONANCE PARAMETERS AND CROSS SECTION FOR $D\bar{D}$ PRODUCTION MEASURED AT SPEAR

There are several measurements of the $\psi(3770)$ resonance parameters. Table I summarizes the measured values of the $\psi(3770)$ resonance parameters by the MARK-I [8], DELCO [9] and MARK-II [10] experiments at the SPEAR, and the world average of the parameters given by Particle Data Group [1].

The production of $\psi(3770)$ resonance in the e^+e^- annihilation can be described by bare Breit-Wigner cross section

TABLE I: Comparison of the measured $\psi(3770)$ resonance parameters from different experiments.

Experiment	M (MeV)	Γ_{tot} (MeV)	Γ_{ee} (eV)
MARK-I [8]	3772±6	28±5	345±85
DELCO [9]	3770±6	24±5	180±60
MARK-II [10]	3764±5	23.5±5.0	276±50
PDG2004 [1]	3769.9 ± 2.5	23.6±2.7	260±40

$$\sigma^{\text{bare}}_{\psi(3770)}(E) = \frac{12\pi\Gamma^0_{ee}\Gamma_{\text{tot}}(E)}{(E^2 - M^2)^2 + M^2\Gamma^2_{\text{tot}}(E)}, \tag{1}$$

where $\Gamma^0_{ee} = \Gamma_{ee}/(1 + \delta_{\text{VP}})$, M and Γ_{ee} are the mass and leptonic width of the $\psi(3770)$ resonance respectively; E is the center-of-mass energy; $\Gamma_{\text{tot}}(E)$ is chosen to be energy dependent [3]. At the peak of the $\psi(3770)$ resonance, the bare cross section for the $\psi(3770)$ production is given by

$$\sigma^{\text{bare}}_{\psi(3770)} = \frac{12\pi}{M^2(1 + \delta_{\text{VP}})}B(\psi(3770) \to e^+e^-) \tag{2}$$

where the $B(\psi(3770) \to e^+e^-)$ is the branching fraction for $\psi(3770) \to e^+e^-$ and $(1 + \delta_{\text{VP}})$ is a correction factor to correct the increased amount in the leptonic width due to the vacuum polarization effect including both leptonic and hadronic terms. In the energy region from charm threshold to 4.14 GeV, $(1 + \delta_{VP})$ varies by less than $\pm 2\%$ [3]. In this section, we treat it as a constant of

$$(1 + \delta_{\text{VP}}) = 1.047 \pm 0.024. \tag{3}$$

Inserting the mass and the purely leptonic branching fraction [1] of $\psi(3770)$ into Eq. (2) we obtain the bare cross section for $\psi(3770)$ production to be

$$\sigma^{\text{bare}}_{\psi(3770)}|_{\text{peak}} = (11.0 \pm 1.7) \quad \text{nb} \tag{4}$$

MARK-III measured the observed cross section [11] for $D\bar{D}$ production at center-of-mass energy $\sqrt{s} = 3.768$ GeV to be $\sigma^{obs}_{D\bar{D}} = 5.0 \pm 0.5$ nb [11]. At this energy, the cross section is reduced by a factor of about 0.734 [18] due to initial state radiation and photon vacuum polarization effects (see section V for more detail). After correcting the observed cross section $\sigma^{obs}_{D\bar{D}}$ for the radiative effects, we obtain the bare cross section for $D\bar{D}$ production to be

$$\sigma^B_{D\bar{D}} = 6.8 \pm 0.7 \quad \text{nb}. \tag{5}$$

The large discrepancy between $\sigma_{\psi(3770)}$ and $\sigma_{D\bar{D}}$ indicates that either, contrary to what is generally expected, $\psi(3770)$ could substantially decay into non$-D\bar{D}$ final states or the measured cross sections for $D\bar{D}$ and $\psi(3770)$ production suffer from large systematic shifts. Otherwise, there might exist some other effects which are responsible for the discrepancy. If we simply calculate the branching fraction for $\psi(3770) \to non - D\bar{D}$ based on the above bare cross sections for $\psi(3770)$ and $D\bar{D}$ production, we obtain

$$B(\psi(3770) \to non - D\bar{D}) = (38.2 \pm 11.5)\%. \tag{6}$$

This value is obtained based on the different measurements at the SPEAR. However, people suspected that the large discrepancy could be due to systematic shift in normalization, since no experiment has measured the cross sections for both the $\psi(3770)$ and $D\bar{D}$ production simultaneously.

The best way to solve this open question is to measure both the bare cross sections for $\psi(3770)$ and $D\bar{D}$ production from the same experiment. The new measurements of the $\psi(3770)$ resonance parameters and the cross sections for $D\bar{D}$ production from BES-II experiment supply one an opportunity to clear the situation.

III. $\psi(3770)$ RESONANCE PARAMETERS MEASURED BY BES-II

BES Collaboration recently reported the results on measurements of the $\psi(3770)$ resonance parameters [5] with a higher precision. Table II summarizes the measured values [5], where the errors are the combined statistical and systematic errors together. The paper [5] also reports the cross section for $\psi(3770)$ production at its peak to be

$$\sigma^{\text{prd}}_{\psi(3770)} = 9.07 \pm 0.82 \quad \text{nb}. \tag{7}$$

This value of the cross section includes the contribution from vacuum polarization effect. After correcting the vacuum polarization effect with the factor given by Eq. (3), we obtain the bare cross section for $\psi(3770)$ production at the peak of the resonance to be

$$\sigma^{\text{bare}}_{\psi(3770)} = 8.66 \pm 0.81 \quad \text{nb}, \tag{8}$$

where the erorr includes the uncertainty in the correction to the vacuum polarization effect.

TABLE II: The measured $\psi(3770)$ resonances parameters from BES-II experiment.

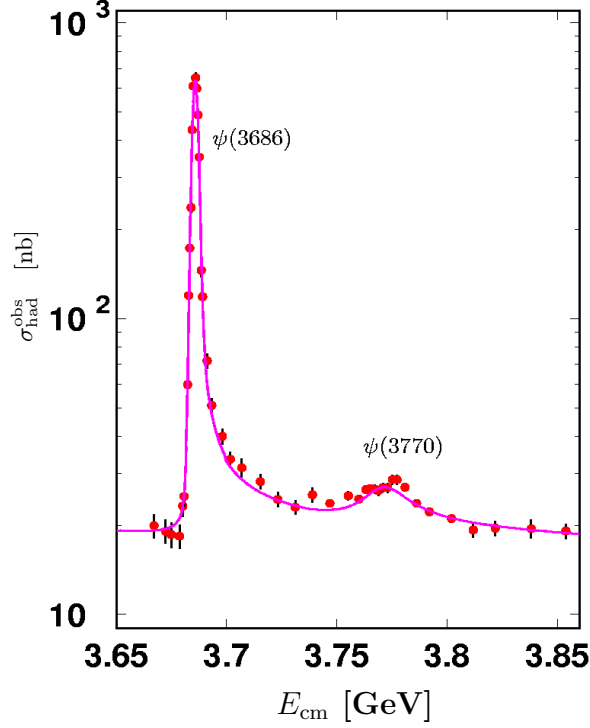| Resonance	M (MeV)	Γ_{tot} (MeV)	Γ_{ee} (eV)
$\psi(3770)$	3772.3 ± 1.0	25.5 ± 3.1	224 ± 31

FIG. 1: The observed inclusive hadronic cross sections vs the nominal c.m. energies; the error bars represent the observed cross sections and the curve is the best fit which is discussed in more details in the Ref. [5].

IV.   CROSS SECTIONS FOR $D^0\bar{D}^0$, D^+D^- AND $D\bar{D}$ PRODUCTION MEASURED BY BES-II EXPERIMENT AT $\sqrt{s} = 3.773$ GEV

With single and double tag analysis method [4], BES Collaboration analyzed the invariant mass spectra of $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$, $K^-\pi^+\pi^+$, $K_S^0\pi^+$, $K_S^0\pi^+\pi^+\pi^-$, $K^-K^+\pi^+$, $K^-K^+\pi^+$, $K_S^0K^+$, $K^-\pi^+\pi^+\pi^0$ and $K_S^0\pi^+\pi^0$ combinations for single tag analysis, and the mass spectra of $K^-\pi^+$, $K^-\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^-$ and $K^-\pi^+\pi^+$ combinations for double tag analysis to measure the observed cross sections for $D^0\bar{D}^0$ and D^+D^- production at $\sqrt{s} = 3.773$ GeV. They obtained the cross sections for $D^0\bar{D}^0$, D^+D^- and $D\bar{D}$ production at this energy point to be [4]

$$\sigma^{\mathrm{obs}}_{D^0\bar{D}^0} = (3.47 \pm 0.32 \pm 0.21) \text{ nb}, \tag{9}$$

$$\sigma^{\mathrm{obs}}_{D^+D^-} = (2.46 \pm 0.33 \pm 0.20) \text{ nb}, \tag{10}$$

$$\sigma^{\mathrm{obs}}_{D\bar{D}} = (5.93 \pm 0.46 \pm 0.35) \text{ nb}, \tag{11}$$

where the first error is statistical and second systematic. These values of the cross sections are consistent with that measured by BES Collaboration based on single tag analysis [3], and consistent with that measured by CLEO [6] within error.

To obtain the bare cross sections for $D^0\bar{D}^0$, D^+D^- and $D\bar{D}$ production, the observed cross sections have to be corrected for the radiative effects.

V.   RADIATIVE CORRECTIONS

In any e^+e^- colliding beam experiment, the electron (positron) always radiates at the interaction point because of the potential of the positron (electron). Since this radiation (Bremsstrahlung) carries energy away, the actual center-of-mass energy for the e^+e^- annihilation is reduced by Bremsstrahlung to $\sqrt{s(1-x)}$, where xE_{beam} is the total energy of the emitted photons. The Bremsstrahlung is principally responsible for the distortions to the bare resonance line shape, while the self energy of the electron and positron and the vertex corrections to the initial state affect the overall factors to change the scale of the cross section. All of these corrections are called Initial State Radiation (ISR) corrections. The bare cross section for $D\bar{D}$ production at the energy of 3.773 GeV can be obtained by correcting the observed cross section for the effects of the ISR and vacuum polarization.

The observed cross section, σ^{obs}, at the nominal energy $\sqrt{s}$ can be written as a convolution of the bare cross section $\sigma^B(s(1-x))$ and a sampling function $F(x,s)$ [12] [3],

$$\sigma^{\text{obs}}(s) = \int_0^1 dx F(x,s) \frac{\sigma^B(s(1-x))}{|1 - \Pi(s(1-x))|^2}, \tag{12}$$

in which the $|1-\Pi(s(1-x))|^{-2}$ is due to the photon vacuum polarization, the $\Pi(s)$ is the photon vacuum polarization operator including the loops over leptons (e μ and τ) and hadrons [13] [14].

Since we are interested in the $\psi(3770)$ resonance in this analysis, we take the σ^B to be the bare Breit-Wigner cross section as given in Eq. (1), where $\Gamma_{\text{tot}}(E)$ is chosen to be energy dependent and normalized to the total width Γ_{tot} at the peak of the resonance [1] [10]. The $\Gamma_{\text{tot}}(E)$ is defined as [3]

$$\Gamma_{\text{tot}}(E) = \Gamma_{\text{tot}} \frac{\frac{p_{D^0}^3}{1+(rp_{D^0})^2} + \frac{p_{D^\pm}^3}{1+(rp_{D^\pm})^2}}{\frac{p^0{}_{D^0}^3}{1+(rp^0{}_{D^0})^2} + \frac{p^0{}_{D^\pm}^3}{1+(rp^0{}_{D^\pm})^2}}, \tag{13}$$

where p_D^0 is the momentum of the D mesons produced at the peak of $\psi(3770)$, p_D is the momentum of the D mesons produced at the c.m. energy $\sqrt{s}$, Γ_{tot} is the width of the $\psi(3770)$ at the peak, and r is the interaction radius which was set to be 0.5 fm in the analysis. In the calculation of the bare cross section, the $\psi(3770)$ resonance parameters $M = 3772.3 \pm 1.0$ MeV; $\Gamma_{\text{tot}} = 25.5 \pm 3.1$ MeV and $\Gamma_{ee} = 0.224 \pm 0.031$ keV measured by BES Collaboration [5] were used.

The $\psi(3770)$ width (~ 25 MeV) is much large than the energy spread (~ 1.37 MeV) of the BEPC. So the effect of the beam energy spread on the cross section could be ignored. The $\psi(3770)$ is generally assumed to decay exclusively into $D\bar{D}$. Taking these considerations, the observed cross section of Eq. (12) should be replaced by

$$\sigma^{\text{obs}}(s) = \int_0^{1-4M_D^2/s} dx F(x,s) \frac{\sigma^B(s(1-x))}{|1 - \Pi(s(1-x))|^2} \tag{14}$$

in calculation of the radiative corrections. The correction factor for the radiative effects is given by

$$g = \frac{\sigma^{\text{obs}}}{\sigma^B}. \tag{15}$$

Figure 2 shows the factor of the radiative corrections as a function of the nominal center-of-mass energy. At the center-of-mass energy $\sqrt{s} = 3.773$ GeV, the factor is

$$g = 0.768 \pm 0.020, \tag{16}$$

where the error is the uncertainty arising from the errors of the $\psi(3770)$ resonance parameters and the uncertainty in vacuum polarization correction.

VI.   BARE CROSS SECTION FOR $D\bar{D}$ PRODUCTION

The bare cross sections for $D^0\bar{D}^0$, D^+D^- and $D\bar{D}$ production are obtained by dividing the observed cross sections by the factor $g = 0.768 \pm 0.020$ of the radiative corrections. At $\sqrt{s} = 3.773$ GeV, the bare cross sections are

$$\sigma_{D^0\bar{D}^0}^{\text{bare}} = (4.52 \pm 0.42 \pm 0.30) \text{ nb}, \tag{17}$$
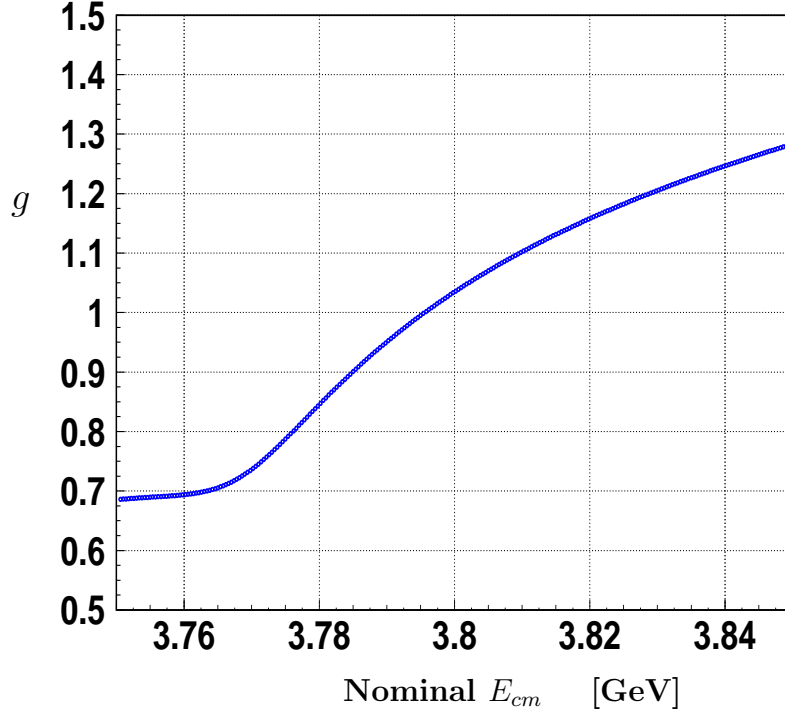
FIG. 2: The factor of radiative corrections as a function of the nominal center-of-mass energy.

$$\sigma_{D^+D^-}^{\text{bare}} = (3.20 \pm 0.43 \pm 0.27)\ \text{nb}, \tag{18}$$

and

$$\sigma_{D\bar{D}}^{\text{bare}} = (7.72 \pm 0.60 \pm 0.50)\ \text{nb}, \tag{19}$$

where the first error is statistical and the second systematic which include the uncertainty in the factor of the radiative corrections ($\sim 2.6\%$).

VII.   BRANCHING FRACTIONS FOR $\psi(3770) \to D\bar{D}$ AND $\psi(3770) \to non - D\bar{D}$

Dividing the bare cross sections for $D^0\bar{D}^0$, D^+D^- and $D\bar{D}$ production by the bare cross section for $\psi(3770)$ prodcution given by Eq. (8), we obtain the branching fractions to be

$$B(\psi(3770) \to D^0\bar{D}^0) = (52.2 \pm 4.8 \pm 5.5)\%, \tag{20}$$

$$B(\psi(3770) \to D^+D^-) = (37.0 \pm 5.0 \pm 4.3)\%, \tag{21}$$

$$B(\psi(3770) \to D\bar{D}) = (89.1 \pm 6.9 \pm 9.2)\% \tag{22}$$

and the latter one implies

$$B(\psi(3770) \to non - D\bar{D}) = (10.9 \pm 6.9 \pm 9.2)\%, \tag{23}$$

where the first error is statistical and second the uncancelled systematic uncertainty. The systematic uncertainties in luminosity measurement and in the radiative correction factor are canceled in the determinations of the branching

fractions. Using the total width of $\psi(3770)$ resonance $\Gamma_{\text{tot}}^{\psi(3770)} = 25.5 \pm 3.1$ MeV measured by the BES Collaboration, this branching fraction corresponds to a partial width of

$$\Gamma(\psi(3770) \to non - D\bar{D}) = (2.8 \pm 1.8 \pm 2.4) \quad \text{MeV}, \tag{24}$$

where the first error is statistical and second systematic arising from the uncertainty in the measured branching fraction for $\psi(3770) \to non - D\bar{D}$ and the uncertainty in the measured total width of $\psi(3770)$ resonance. Those result in a total observed cross section for $non - D\bar{D}$ final states of $\psi(3770)$ decays at $\sqrt{s} = 3.773$ GeV to be

$$\sigma^{\text{obs}}(\psi(3770) \to non - D\bar{D}) = (0.72 \pm 0.46 \pm 0.62) \quad \text{nb}, \tag{25}$$

where the first error reflects the statistical fluctuation on the measured branching fraction for the decay $\psi(3770) \to non - D\bar{D}$ and the second one reflects all of other uncertainties, such as the systematic uncertainty in the measured branching fraction, the uncertainty in the radiative effect corrections and the uncertainty in the total width of $\psi(3770)$ resonance.

VIII. SUMMARY AND DISCUSSION

Based on the recent publications about $\psi(3770)$ and $D\bar{D}$ production and decays from BES Collaboration and with making some necessary corrections for initial state radiative and vacuum polarization effects, we determined the branching fractions for $\psi(3770) \to D^0 \bar{D}^0, D^+ D^-, D\bar{D}$ to be $(52.2 \pm 4.8 \pm 5.5)\%$, $(37.0 \pm 5.0 \pm 4.3)\%$, and $(89.1 \pm 6.9 \pm 9.2)\%$, respectively. Meanwhile we determined the branching fraction for $\psi(3770) \to non - D\bar{D}$ to be $(10.9 \pm 6.9 \pm 9.2)\%$, corresponding the partial width $\Gamma(\psi(3770) \to non - D\bar{D}) = (2.8 \pm 1.8 \pm 2.4)$ MeV. We also determined the observed cross section for $\psi(3770) \to non - D\bar{D}$ to be $\sigma^{\text{obs}}(\psi(3770) \to non - D\bar{D}) = (0.72 \pm 0.46 \pm 0.62)$ nb at $\sqrt{s} = 3.773$ GeV.

There previously were some estimations on the branching fraction for the decay $\psi(3770) \to non - D\bar{D}$ [2] [15]. These estimations were based on some measurements of the cross sections for $\psi(3770)$ and $D\bar{D}$ production from different experiments [8] [9] [10] [16] [17]. In that case there may be some systematic shifts in the measured values of $\sigma_{\psi(3770)}$ and $\sigma_{D\bar{D}}$ due to different normalizations with luminosities of data sets and Monte Carlo efficiencies. However, all of the physics quantities determined in this letter are based on the measurements from the same experiment, and the cross sections for both the $\psi(3770)$ resonance and $D\bar{D}$ production are transfered into the bare ones by making the necessary corrections for the initial state radiative and vacuum polarization effects. In this case the results of the determined physics quantities would be more reliable.

We are expecting that both BES and CLEO Collaborations will give more precise measurements of the partial width for the decay $\psi(3770) \to non - D\bar{D}$ in the near future.

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